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Remote sensing monitoring of the recent rapid increase in cultivation activities and its effects on desertification in the Mu Us Desert, China

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Abstract: The recent ecological improvement in the Mu Us Desert of China, largely attributed to large-scale afforestation projects, has created new opportunities for cultivation activities. However, the subsequent rapid increase in reclamation on desertification land and its impact on desertification have raised concerns. In this study, we first extracted data on cultivated land and desertification land in 1975, 1990, 2000, 2005, 2010, 2015, and 2020 through the human-computer interaction visual interpretation method. By overlaying the cultivated land dynamics and desertification land, we subsequently explored the effect of cultivation activities on desertification in the Mu Us Desert during the six periods from 1975 to 2020 (1975–1990, 1990–2000, 2000–2005, 2005–2010, 2010–2015, and 2015–2020). The results showed that cultivated land in the Mu Us Desert showed a fluctuating and increasing trend from 3769.26 km² in 1975 to 4865.73 km² in 2020, with 2010 as the turning point for the recent rapid increase. The main contributors included the large and regular patches distributed in Yuyang District and Shenmu of Shaanxi Province, and relatively smaller patches concentrated in Inner Mongolia Autonomous Region. The increased cultivated land from the reclamation on desertification land was dominated by moderate and severe desertification lands, and the decreased cultivated land that was transferred into desertification land as abandoned cultivated land was dominated by slight and moderate desertification lands. The effect of cultivation activities on desertification reversal (average area proportion of 10.61% for reversed desertification land) was greater than that of the development of desertification (average area proportion of 5.82% for developed desertification land). Nevertheless, compared to reversed desertification land, both the significant increase of developed desertification land during the periods of 2000–2005 and 2005–2010 and the insignificant decrease during the periods of 2005–2010, 2010–2015, and 2015–2020 implied a potential remobilization risk. Therefore, this study provides a significant theoretical reference for the formulation of ecological restoration projects and regional macroeconomic development policies by considering the influence of cultivation activities, to ensure the overall environmental stability and sustainability in desertification land where reclamation and abandonment activities have taken place.

Keywords: cultivation activities; desertification land; desertification reversal and development; reclamation; spatial overlay analysis; Mu Us Desert

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1 Introduction

The Mu Us Desert, situated in northern China, exemplifies a typical agro-pastoral ecotone that is highly sensitive and vulnerable to disturbances from cultivation activities (Li et al., 2017; Zhang and Wu, 2020). According to previous studies (Hao and Wu, 2006; Li et al., 2014; Lyu et al., 2020; Zhang et al., 2018; Wang et al., 2023), a growing population has led to a shortage of grain, and some ecological practices reduced the income of farmers and herders. As a result, farmers in the Mu Us Desert region converted large areas of land, which were previously covered with forests, shrubs, and steppe vegetation near desert oases, into cultivated land over the past several decades (Li et al., 2014). In the short term, some of the land reclaimed from desertification has seen a significant increase in the contents of total soil carbon, nitrogen, phosphorus, and organic carbon (Bakr et al., 2012; Shang et al., 2019; Liu et al., 2022), contributing to the achievement of several farmland requisition-compensation balance targets in Shaanxi Province, China (Liu et al., 2022). Nonetheless, cultivation activities, including both the reclamation of desertification land and the abandonment of cultivated land, have emerged as primary drivers of desertification (Shi et al., 2019; Zhou et al., 2020). In fact, the evidence of desertification has been detected in oases and irrigated land within drylands in northern China (Abdulslam et al., 2015; Wang et al., 2020). On the one hand, the wind erosion intensity of cultivated land reclaimed from desertification land has increased exponentially after the transition from grassland and shrub land (Zhou et al., 2020), and the overall greening trend in some areas with cultivation activities has declined, potentially accelerating the emergence of new dust sources due to vegetation loss (Bhattachan et al., 2012; Yuan et al., 2019). On the other hand, increased water consumption for agricultural irrigation has exacerbated water resource challenges in these water-limited regions (Feng et al., 2016; Liu et al., 2022; Zhao et al., 2022), leading to additional ecological concerns such as decreased groundwater levels, diminished water resource carrying capacity, and excessive concentrations of NH_4^+-N, NO_3^--N, and NO_2^--N in groundwater, which in turn pose threats to agricultural livelihoods (Sadeghravesh et al., 2014; Shi et al., 2019; Liu et al., 2022).

Although cultivation activities on desertification land have had notable impacts on desertification, current understanding primarily stems from research conducted on a sample-plot scale (Zhou et al., 2020; Liu et al., 2022). Consequently, the need for large-scale, long-term studies on the effects of cultivation activities is both essential and urgent. The Mu Us Desert, one of China's semi-arid regions most susceptible to desertification (Zhang and Wu, 2020), features cultivated land reclaimed from desertification land that is particularly prone to desertification (Ministry of Natural Resources of the People's Public of China, 2014). This susceptibility, coupled with the recent rise in temperatures, altered precipitation patterns, and increased frequency of extreme weather events that affected agro-ecosystems and pastoral systems (Zhu et al., 2013; Amin et al., 2018), has prompted the selection of the Mu Us Desert as the focus of this study amid the backdrop of unprecedented climate change and intensifying human activities. To clarify the effect of cultivation activities on desertification in the Mu Us Desert, we conducted spatial overlay analysis between desertification land and the increased cultivated land as well as between desertification land and the decreased cultivated land, based on desertification land and land cover datasets extracted from a wide range of Landsat images from 1975 to 2020 (1975, 1990, 2000, 2005, 2010, 2015, and 2020). The results give an insight into decision-making and implementation featuring reasonability, efficiency, and sustainability, thus stabilizing agricultural production and preserving environmental security.

2 Materials and methods

2.1 Study area

Mu Us Desert, as a typical agro-pastoral transition zone, is an ecologically fragile region located in the transitional zone between the Ordos Plateau and the Loess Plateau, China (Xie et al., 2022). It contains Kangbashi District, Uxin Banner, part of Dongsheng District, Otog Front Banner, Otog

Banner, Ejin Horo Banner, Hanggin Banner, and Jungar Banner of Ordos City in southwestern Inner Mongolia Autonomous Region, part of Yuyang District, Shenmu, Hengshan District, Jingbian County, Dingbian County, and Jiaxian County of Yulin City in northern Shaanxi Province, and part of Yanchi County of Wuzhong City in eastern Ningxia Hui Autonomous Region (Fig. 1a), with a total area of 48,289.00 km^2. The distribution of agriculture and animal husbandry shows an obvious regional difference from southeast to northwest, following an opposite elevation distribution trend from 1000 m to 1600 m. The Mu Us Desert has a temperate continental semi-arid climate, with an annual average temperature of 6.0°C–8.5°C and annual precipitation of 250–440 mm. Desertification is the primary ecological and environmental problem in the Mu Us Desert (Shi et al., 2019), with area proportions of 22.25%, 22.64%, 24.41%, and 16.25% for slight, moderate, severe, and serious desertification lands in 2020, respectively (Fig. 1b). Due to a series of projects implemented to combat desertification (Li et al., 2017; Zhang and Wu, 2020), most existing vegetation in the Mu Us Desert is secondary or artificial. Grassland is the main land cover type due to the climatic characteristics, and there exhibits an overall transition of grassland from desert-steppe to steppe and forest-steppe in 2020, with grassland accounting for 40.91% of the total area of the Mu Us Desert. Bare land is the secondary major land cover type, which accounts for 35.16% of the total area, followed by forestland, cultivated land, artificial land, and wetland, with the area proportions of 10.52%, 10.08%, 2.57%, and 0.76%, respectively (Fig. 1a).

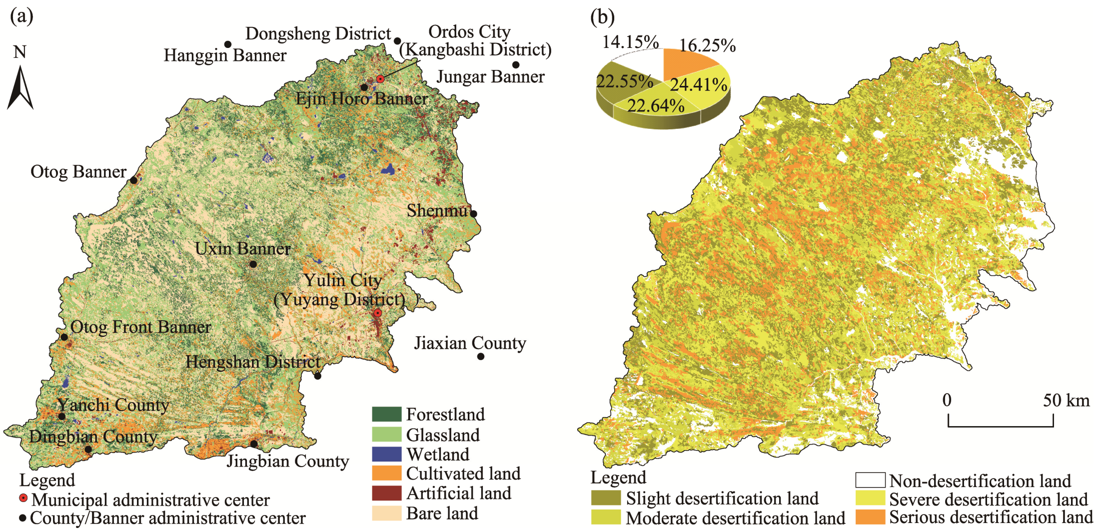

Fig. 1 Spatial distribution of land cover types (a) and different desertification land types (b) in the Mu Us Desert in 2020. The pie chart shows the area proportions of desertification lands and non-desertification land in the Mu Us Desert in 2020.

2.2 Data sources

Landsat images were downloaded through Google Earth Engine (GEE) platform (https://developers.google.com/earthengine/datasets/catalog/landsat), which were surface reflectance images atmospherically corrected using LEDAPS 1.0.0 software (National Aeronautics and Space Administration-Goddard Space Flight Center and the University of Maryland). Specifically, we acquired Landsat MSS images (1975; spatial resolution of 60 m×60 m), ETM images (2000; spatial resolution of 30 m×30 m), TM images (1990, 2005, and 2010; spatial resolution of 30 m×30 m), and OLI images (2015 and 2020; spatial resolution of 30 m×30 m). Landsat MSS images were resampled to 30 m×30 m by the nearest-neighbor method in ArcGIS, thus being compatible with other images. Images with cloud cover of more than 10% were replaced by adjacent years' images during the growing season (from June to September).

2.3 Methods

2.3.1 Extraction method of desertification land and land cover information

We employed the human-computer interaction visual interpretation method to extract desertification land and land cover datasets of the Mu Us Desert in 1975, 1990, 2000, 2005, 2010, 2015, and 2020, using Landsat images during the vegetation growing season from June to September. First, false-color images composited by Landsat MSS bands (6, 5, and 4), TM bands (4, 3, and 2), and OLI bands (5, 4, and 3) (R, G, and B, respectively) were adopted to distinguish surface information clearly (Yan et al., 2017). Then, an object-oriented approach that takes an image object as a basic analysis unit was used to extract desertification land and land cover information in the eCognition Developer 64 V9.0 software (Definiens Imaging company, Munich, Germany) (Li et al., 2017, 2019).

Eventually, we classified the land cover into six categories of forestland, grassland, wetland, cultivated land, artificial land, and bare land (Fig. 1a) based on the classification system in the project of the "status, speed, mechanism and potential of carbon storage in ecosystem" (Zhang et al., 2014). We further divided desertification land into four categories (slight, moderate, severe, and serious desertification lands) according to the percentage of mobile sand area, fractional vegetation cover (FVC), and surface landscape characteristics (Zhai et al., 2020; Xie et al., 2022) (Table 1). In addition, a field investigation conducted in September 2021 verified the interpretation accuracy of desertification land and land cover data, in which the first-level classification accuracy was greater than 95% for both land cover and desertification land data.

Table 1 Criteria for the classification of desertification land

Desertification land types	Percentage of mobile sand area (%)	FVC (%)	Surface landscape characteristics
Slight	<5	>60	Only sporadic mobile dunes are distributed and most areas are still similar to the original landscape.
Moderate	5–25	30–60	This type mainly includes the sheet mobile dunes, coppice dunes, and wind erosion area.
Severe	25–50	10–30	Mobile dunes are distributed in a relatively large area with dense coppice dunes and strong wind.
Serious	>50	<10	Mobile dunes are densely distributed in the whole region, with only annual sandy plants.

Note: FVC, fractional vegetation cover.

FVC, which was used to classify desertification land types, was calculated by Equation 1.

$$\mathrm{FVC}=\frac{\mathrm{NDVI}-\mathrm{NDVI}_{\mathrm{soil}}}{\mathrm{NDVI}_{\mathrm{veg}}-\mathrm{NDVI}_{\mathrm{soil}}}, \tag{1}$$

where, FVC is the fractional vegetation cover (%); NDVI is the Normalized Difference Vegetation Index; $\mathrm{NDVI}_{\mathrm{soil}}$ represents the NDVI value of bare land, i.e., the NDVI value of pixels without vegetation cover; and $\mathrm{NDVI}_{\mathrm{veg}}$ represents the NDVI value of pure vegetation, i.e., the NDVI value of pixels completely covered by vegetation (Jiapaer et al., 2011). Generally, $\mathrm{NDVI}_{\mathrm{soil}}$ and $\mathrm{NDVI}_{\mathrm{veg}}$ for a given period are calculated with 5% of confidence, in which the NDVI value at a cumulative percentage of 5% is $\mathrm{NDVI}_{\mathrm{soil}}$ and the NDVI value at a cumulative percentage of 95% is $\mathrm{NDVI}_{\mathrm{veg}}$.

2.3.2 Spatial overlay analysis

Spatial overlay analysis involves superimposing two or more layers of distinct geographic features within the same area, using a shared reference coordinate system. This process generates new, combined spatial and attribute data for the region, as well as establishes spatial relationships between the geographic features (Ding et al., 2018). In this research, we used ArcGIS 10.2 software to perform spatial overlay analysis between desertification land and the cultivated land dynamics (the increased cultivated land and the decreased cultivated land). This allowed us to obtain datasets for both the increased cultivated land from the reclamation on desertification land and the decreased cultivated land that was transferred into desertification land as abandoned cultivated land during the six time periods between 1975 and 2020 (1975–1990, 1990–2000,

2000–2005, 2005–2010, 2010–2015, and 2015–2020) (Fig. 2). More specifically, the increased cultivated land from the reclamation on desertification land was determined by overlaying the increased cultivated land data for the six time periods (1975–1990, 1990–2000, 2000–2005, 2005–2010, 2010–2015, and 2015–2020) with desertification land data from 1975, 1990, 2000, 2005, 2010, and 2015. The decreased cultivated land that was transferred into desertification land as abandoned cultivated land was obtained by overlaying the decreased cultivated land data for the six time periods (1975–1990, 1990–2000, 2000–2005, 2005–2010, 2010–2015, and 2015–2020) with desertification land data from 1990, 2000, 2005, 2010, 2015, and 2020.

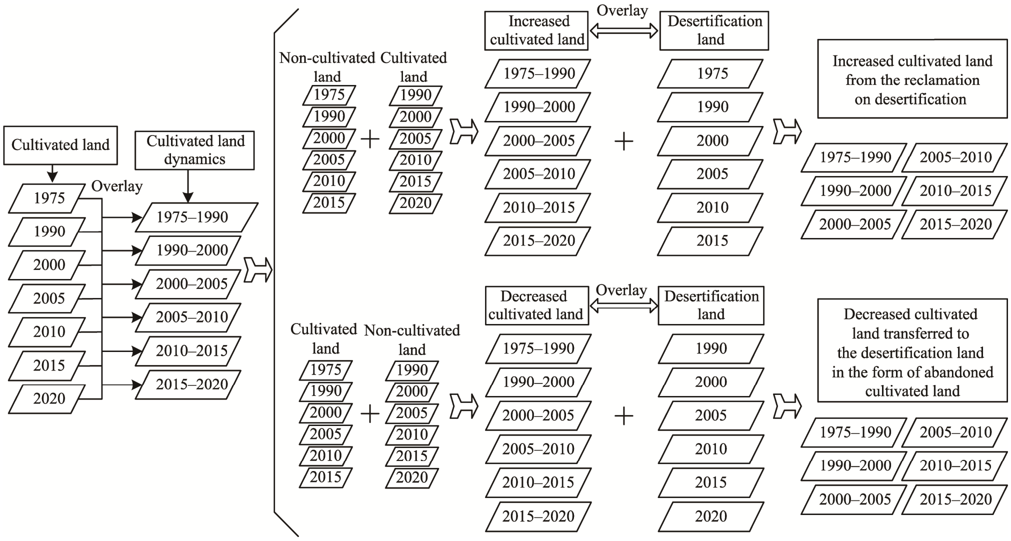

Fig. 2 Spatial overlay analysis between desertification land and the cultivated land dynamics (the increased cultivated land and the decreased cultivated land) during the six periods from 1975 to 2020

Meanwhile, to explore the overall impact of cultivation activities on desertification during the six time periods between 1975 and 2020 (1975–1990, 1990–2000, 2000–2005, 2005–2010, 2010–2015, and 2015–2020), we identified the dynamics of desertification land that can reflect the changes among different desertification land types as well as between desertification land types and non-desertification land in the areas of the increased cultivated land from the reclamation on desertification land and the decreased cultivated land that was transferred into desertification land as abandoned cultivated land. In detail, reversed desertification land and developed desertification land were the two main dynamic types of desertification land, which could be further categorized into four types, i.e., the lighter degree of desertification land, disappeared desertification land, severer degree of desertification land, and appeared desertification land (Wang, 2013; Xie et al., 2022) (Table 2).

Table 2 Classification system of the dynamics of desertification land

Dynamic types of desertification land		Transformation types of desertification land
Reversed desertification land	Lighter degree of desertification land	Serious desertification land was transferred to severe, moderate, and slight desertification lands. Severe desertification land was transferred to moderate and slight desertification lands. Moderate desertification land was transferred to slight desertification land.
	Disappeared desertification land	Any of the four desertification land types were transferred to non-desertification land.
Developed desertification land	Severer degree of desertification land	Slight desertification land was transferred to moderate, severe, and serious desertification lands. Moderate desertification land was transferred to severe and serious desertification lands. Severe desertification land was transferred to serious desertification land.
	Appeared desertification land	Non-desertification land was transferred to any of the four desertification land types.

3 Results

3.1 Spatiotemporal dynamics in cultivated land

Cultivated land in the Mu Us Desert covered an arc-shaped region from northeast to southwest, which was mainly distributed in Yulin City, Ejin Horo Banner, Otog Front Banner, and Yanchi County (Fig. 3a), and cultivated land presented an overall change trend of "increasing-increasing-decreasing-decreasing-increasing-increasing" from 1975 to 2020, with the years 2000 and 2010 as the two turning points (Fig. 3b–g; Table 3). From the perspective of the different provinces and autonomous regions, Shaanxi Province had the highest area proportion of cultivated land, and the area showed a trend of "decreasing-increasing-decreasing-decreasing-increasing-increasing". The area proportion of cultivated land in Inner Mongolia Autonomous Region was relatively lower, and the area showed a changing trend of "increasing-increasing-decreasing-increasing-increasing-increasing" from 1975 to 2020. With a minimum area proportion of cultivated land, Ningxia Hui Autonomous Region showed an overall trend of "increasing-increasing-decreasing-increasing-increasing-decreasing" in its area of cultivated land (Table 3).

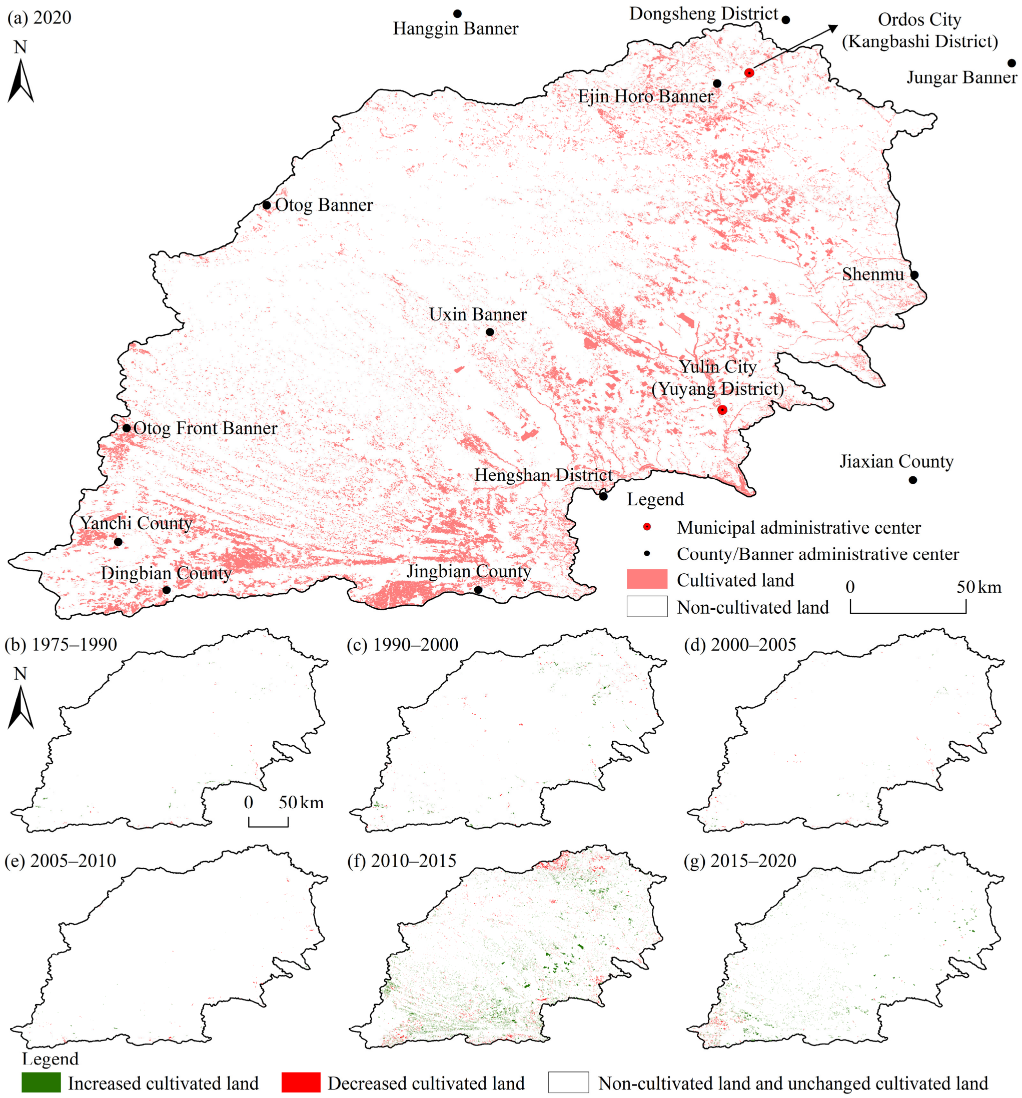

Fig. 3 Spatial distribution of cultivated land in the Mu Us Desert in 2020 (a) and its dynamics during the six periods of 1975–1990 (b), 1990–2000 (c), 2000–2005 (d), 2005–2010 (e), 2010–2015 (f), and 2015–2020 (g)

Table 3 Dynamics of cultivated land in the Mu Us Desert from 1975 to 2020

Year	Ningxia Hui Autonomous Region		Inner Mongolia Autonomous Region		Shaanxi Province		Total area (km^2)
	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	
1975	165.45	4.39	1577.41	41.85	2026.40	53.76	3769.26
1990	174.04	4.60	1580.07	41.80	2026.08	53.60	3780.20
2000	182.30	4.77	1586.75	41.51	2053.62	53.72	3822.67
2005	178.57	4.71	1585.26	41.83	2025.93	53.46	3789.76
2010	179.12	4.75	1587.30	42.13	2000.80	53.11	3767.23
2015	182.13	3.99	2072.44	45.39	2311.24	50.62	4565.80
2020	171.83	3.53	2253.25	46.31	2440.66	50.16	4865.73

In detail, the total cultivated land area in the Mu Us Desert increased from 3769.26 km^2 in 1975 to 3822.67 km^2 in 2000, then declined to a minimum value of 3767.23 km^2 in 2010, and finally jumped to a maximum value of 4865.73 km^2 in 2020. The increased cultivated land from 1975 to 2000 was mainly distributed in the central part of Ejin Horo Banner and Yanchi County, the western part of Shenmu, and the northern part of Dingbian County, while the slightly decreased cultivated land mainly covered the northeastern part of Dingbian County and the central part of Shenmu. From 2000 to 2010, the decreased cultivated land was mainly distributed in Dingbian County, and sporadically dotted in Yanchi County and the southern part of Uxin Banner. From 2010 to 2020, the increased cultivated land was mainly distributed in Yuyang District and Shenmu in the shape of relatively large and regular patches (Fig. 4). In addition, Dingbian County, Jingbian County, Hengshan District, Jiaxian County, Ejin Horo Banner, Uxin Banner, and Otog Front Banner all performed an obvious increase in cultivated land with a form of relatively smaller patches, while Yanchi County, the northern part of Ejin Horo Banner, and the western part of Dingbian County showed a decrease in cultivated land.

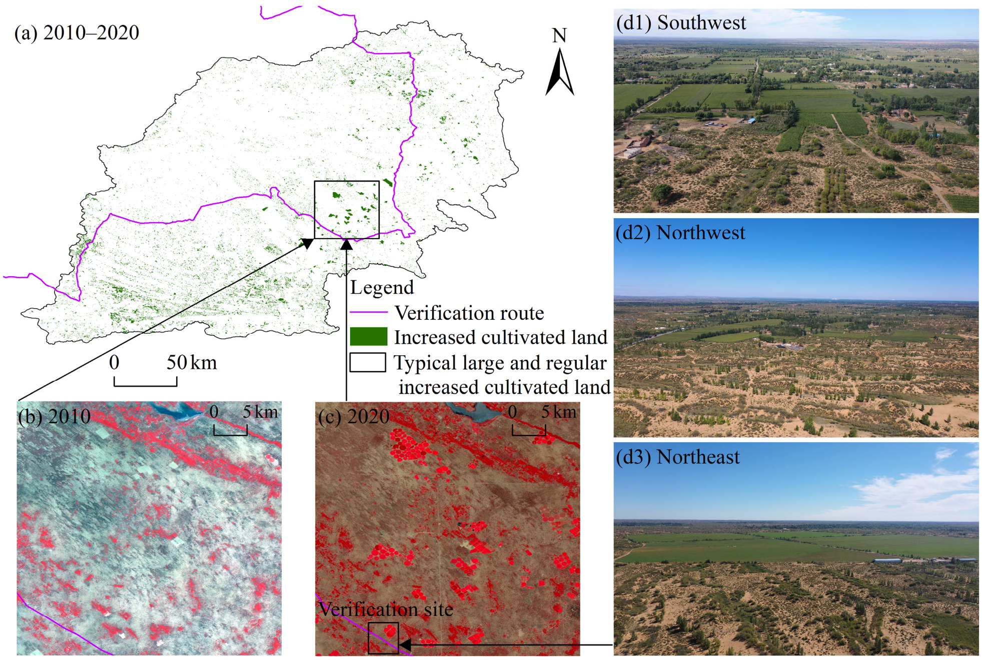

Fig. 4 Spatial distribution of the increased cultivated land in the Mu Us Desert from 2010 to 2020 (a) and false color images displaying the local variation of cultivated land in Yuyang District from 2010 (b) to 2020 (c), as well as pictures showing the verification site (d1–d3). (d1), picture showing the southwest of verification site in 2020; (d2), picture showing the northwest of verification site in 2020; (d3), picture showing the northeast of verification site in 2020. False color images of Figure 4b and c are from Landsat TM and Landsat OLI, respectively.

3.2 Reclamation on desertification land

As one of China's typical deserts, the adjacent distribution of cultivated land and desertification land is obvious in the Mu Us Desert (Fig. 1), and the overall increasing trend of the increased cultivated land makes it necessary to further discuss whether and to what extent the neighboring different desertification land types have been reclaimed.

The statistical results of the spatial overlay analysis between desertification land and the increased cultivated land indicated that the trend of the increased cultivated land from the reclamation on desertification land was consistent with that of the total cultivated land. Its area reached the minimum value of 8.26 km^2 during 2005–2010, while the maximum area of 1147.50 km^2 occurred during 2010–2015 (Fig. 5). Moderate and severe desertification lands constituted the primary source of the increased cultivated land from the reclamation on desertification land during the six periods from 1975 to 2020, with average area proportions of 18.11% and 17.58%, respectively. Slight desertification land also dominated during 1975–1990, 2005–2010, 2010–2015, and 2015–2020, with an average area proportion of 16.05%. Serious desertification land dominated only during 2000–2005. Therefore, desertification land with a relatively lower desertification degree was the primary source of the increased cultivated land from the reclamation on desertification land.

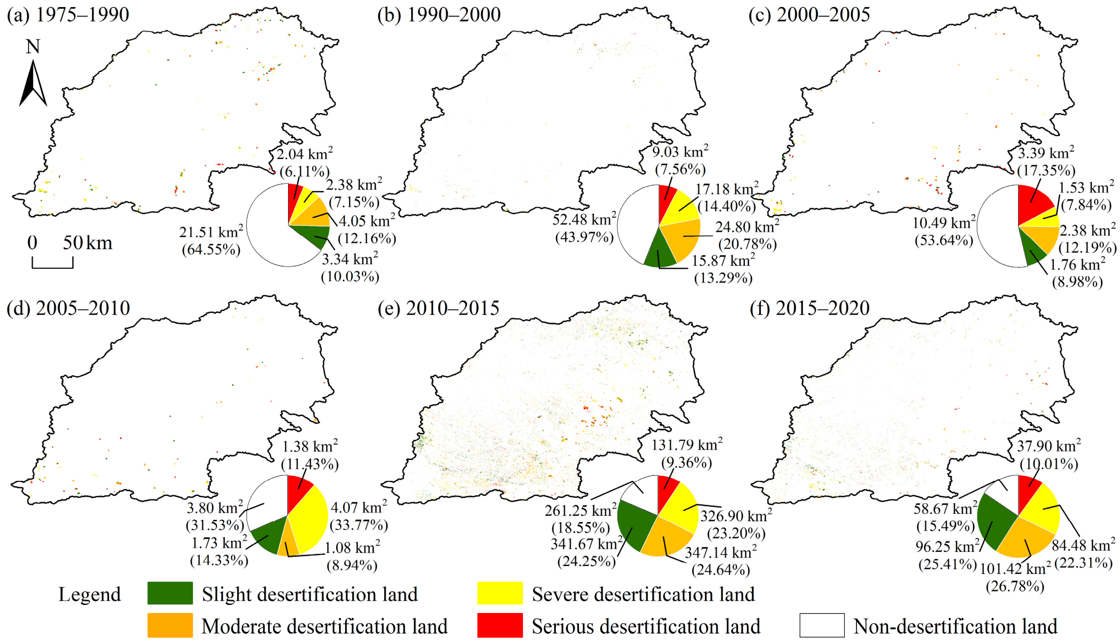

Fig. 5 Spatial distribution of the increased cultivated land from the reclamation on desertification land in the Mu Us Desert during the six periods from 1975 to 2020. (a), 1975–1990; (b), 1990–2000; (c), 2000–2005; (d), 2005–2010; (e), 2010–2015; (f), 2015–2020. The pie charts show the area and area proportion of each desertification land type in the increased cultivated land in the corresponding period.

Moreover, a relatively wider distribution of the increased cultivated land from the reclamation on desertification land could be found during the three periods of 1990–2000, 2010–2015, and 2015–2020 (Fig. 5). Specifically, during 1990–2000, moderate and severe desertification lands were dominated in the increased cultivated land from the reclamation on desertification land, accounting for 20.78% and 14.40%, respectively, and the increased cultivated land from the reclamation on desertification land was mainly concentrated in Jingbian County and Dingbian County on the southern edge of the Mu Us Desert. Instead, slight and moderate desertification lands with area proportion ranging from 24.25% to 26.78% were the primary desertification land types during 2010–2015 and 2015–2020. The distribution of the increased cultivated land from

the reclamation on desertification land was concentrated in the southeastern part of the Mu Us Desert, including Yuyang District with a large windy beach area along the Great Wall, which was regarded as the primary land consolidation and development zone in the general land use planning of Shaanxi Province from 2006 to 2020. Dingbian County, Shenmu, Hengshan District, and Jingbian County in Shaanxi Province also had a partial distribution, and the sporadic distribution can also be observed in the southern part of Uxin Banner and the southwestern part of Otog Front Banner in Inner Mongolia Autonomous Region.

3.3 Desertification of abandoned cultivated land

Under natural geographic conditions, the carrying capacity of cultivated land is limited. The increasing trend of the decreased cultivated land area (Fig. 3) makes it thus necessary to find out whether and to what extent the decreased cultivated land is desertified again and becomes desertification land.

The statistical results of the spatial overlay analysis between desertification land and the decreased cultivated land revealed that the trend of the decreased cultivated land that was transferred into desertification land as abandoned cultivated land was also consistent with the total cultivated land. Its area reached the maximum value of 426.43 km^2 between 2010 and 2015, while the minimum value of 5.29 km^2 occurred between 1975 and 1990 (Fig. 6). Slight and moderate desertification lands were the primary desertification land types of the decreased cultivated land that was transferred into desertification land as abandoned cultivated land for the six periods from 1975 to 2020, with average area proportions of 12.44% and 15.41%, respectively. Severe desertification land also dominated during 1975–1990 and 2005–2010, accounting for 9.60% and 9.25%, respectively. As a result, desertification land with relatively lower desertification degree was the primary category of the decreased cultivated land that was transferred into desertification land as abandoned cultivated land.

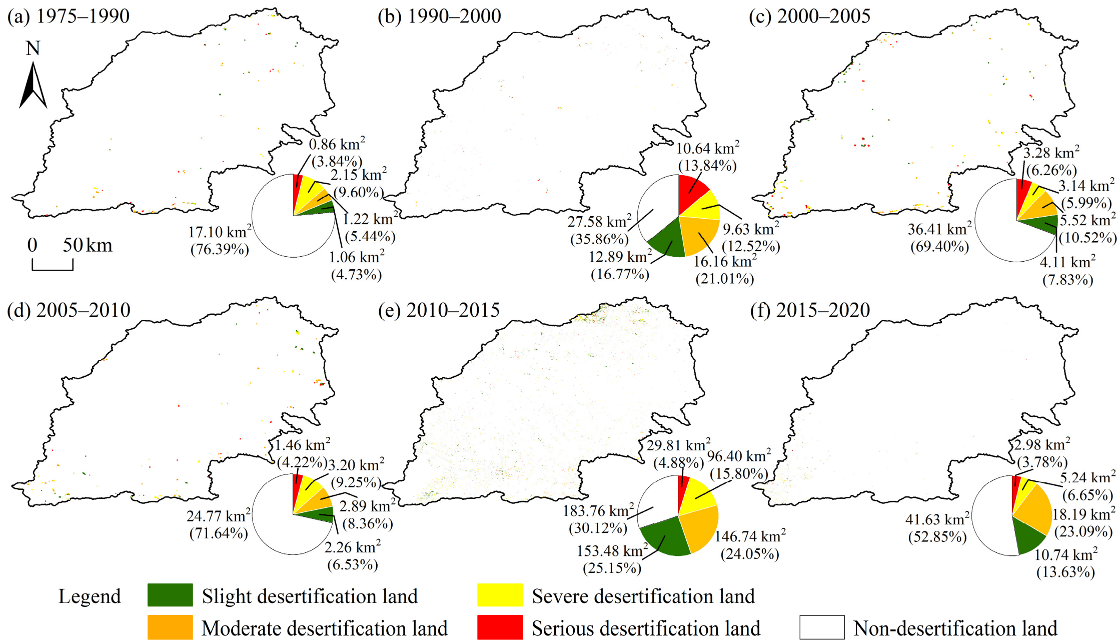

Fig. 6 Spatial distribution of the decreased cultivated land that was transferred into desertification land as abandoned cultivated land in the Mu Us Desert during the six periods from 1975 to 2020. (a), 1975–1990; (b), 1990–2000; (c), 2000–2005; (d), 2005–2010; (e), 2010–2015; (f), 2015–2020. The pie charts show the area and area proportion of each desertification land type in the decreased cultivated land in the corresponding period.

A relatively wider distribution of the decreased cultivated land that was transferred into desertification land as abandoned cultivated land could be found during the same three periods of

1990–2000, 2010–2015, and 2015–2020, and slight and moderate desertification lands were the primary desertification land types, with area proportion ranging from 13.63% to 25.15% (Fig. 6). Specifically, from 1990 to 2000, desertification land was concentrated in Ejin Horo Banner and the central part of Otog Banner in the southwest of the Mu Us Desert, and was sporadically distributed in the northern part of Shenmu in the northeast of the Mu Us Desert. From 2010 to 2015, desertification land was sporadically distributed in the cultivated land distribution area. A relatively dense distribution of the decreased cultivated land could be found in Kangbashi District and the northern part of Ejin Horo Banner. From 2015 to 2020, it was mostly distributed in Yanchi County and the western part of Otog Front Banner.

3.4 Effects of cultivation activities on desertification

Desertification land area decreased as a source of the increased cultivated land from the reclamation on desertification land, but also increased due to the decreased cultivated land that was transferred into desertification land as abandoned cultivated land. Therefore, it is crucial to examine desertification dynamics in the areas of the increased cultivated land from the reclamation on desertification land and the decreased cultivated land that was transferred into desertification land as abandoned cultivated land to better understand the overall impact of cultivation activities on desertification.

In this study, cultivation activities showed a greater impact on desertification reversal than on desertification development, with average area proportion of 10.61% for reversed desertification land and 5.82% for developed desertification land during the six periods from 1975 to 2020 (Fig. 7). In detail, the dynamics of desertification in the total area of the changed cultivated land (reclamation on desertification land and desertification of abandoned cultivated land) was converted from desertification development in the first two periods to desertification reversal in the following four periods. The area proportion of reversed desertification land first increased and then decreased (with 2010–2015 as the turning period), and exhibited a trend of "increasing-increasing-increasing-decreasing-decreasing" during the six periods from 1975 to 2020. The developed desertification land exhibited an overall trend of "increasing-decreasing

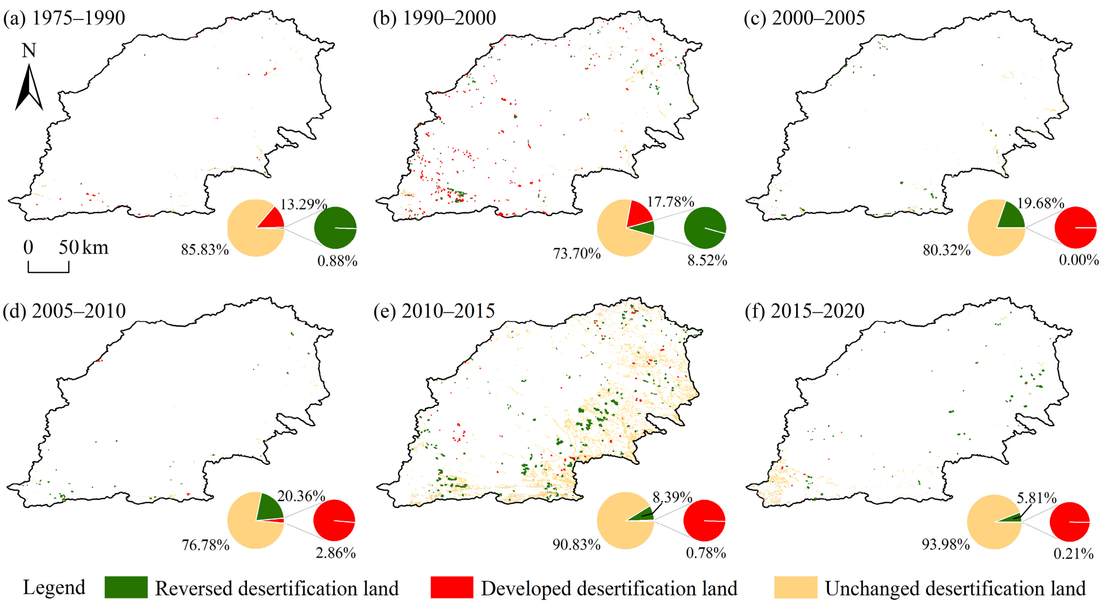

Fig. 7 Spatial distribution of reversed and developed desertification lands in the total area of the changed cultivated land (reclamation on desertification land and desertification of abandoned cultivated land) during the six periods from 1975 to 2020. (a), 1975–1990; (b), 1990–2000; (c), 2000–2005; (d), 2005–2010; (e), 2010–2015; (f), 2015–2020. The pie charts show the area proportion of reversed and developed desertification lands as well as non-desertification land in the corresponding period.

-increasing-decreasing-decreasing" from 1975 to 2020, which showed a similar trend of "increasing-decreasing-decreasing" as reversed desertification land since the period of 2005–2010, and the significant change was observed between the two periods (2000–2005 and 2005–2010) and the last three periods (2005–2010, 2010–2015, and 2015–2020). The two periods (2000–2005 and 2005–2010) exhibited a significant increase in developed desertification land and a relatively smaller increase in reversed desertification land. The last three periods (2005–2010, 2010–2015, and 2015–2020) presented a significant decrease in reversed desertification land and an insignificant decrease in developed desertification land.

Developed desertification land dominated in the first two periods, while reversed desertification land in the following four periods (Fig. 7). In detail, developed desertification land was concentrated in the southwestern, northern, and western edges of the Mu Us Desert during 1975–1990 and 1990–2000, with a wider distribution in Dingbian County, Jingbian County, Otog Front Banner, and the southern part of Uxin Banner. The southeast of the Mu Us Desert became the main distribution area of developed desertification land during 2010–2020, which was mainly covered by reversed desertification land. In particular, reversed desertification land during 2010–2015 was mainly distributed in Yuyang District in a large and regular form, which was also observed in Shenmu during 2015–2020.

4 Discussion

The total cultivated land area in the Mu Us Desert reached a sub-peak in 2000 (Fig. 3), and cultivation activities aggravated the development of desertification (Fig. 7). On the one hand, both the implementation of the household contract responsibility system with remuneration linked to output in the 1980s and the increasing population size directly lead to the occurrence of the over-cultivation (Li et al., 2017; Fen et al., 2018). On the other hand, the rise in temperature and the fluctuating decline of precipitation also made a certain contribution to the development of desertification before 2000 (Fen et al., 2018; Xie et al., 2022). The implementation of the fourth phase of the Three-North Shelterbelt Project and the Grain for Green Program has converted a large amount of cultivated land into forestland and grassland since 2000 (Chen et al., 2015; Li et al., 2017), and the area of cultivated land reached 3767.23 km^2 by 2010. As a result, desertification was changed from development to reversal as a whole (Fig. 7). Since 2010, large and regular patches of cultivated land appeared on the windy beach area along the Great Wall (Fig. 4), which was regarded as the primary land consolidation and development zone in the general land use planning of Shaanxi Province from 2006 to 2020 (Shi et al., 2019; Zhou et al., 2020; Liu et al., 2022). Coupled with the improved ecological environment through large-scale afforestation projects, the warming and wetting climatic conditions (Wang et al., 2022), and the population expansion and their demand for food (Li et al., 2019), the area of cultivated land thus reached its maximum value of 4865.73 km^2 in 2020. In a word, the overall change trend of cultivated land was consistent with the findings in previous research (Li et al., 2017).

However, the Mu Us Desert is located in a typical ecologically fragile area, and despite its relatively superior planting conditions compared with other sandy lands, such a large-scale reclamation may lead to serious environmental problems (Shi et al., 2019), especially the potential remobilization risk in the increased cultivated land from the reclamation on desertification land and the decreased cultivated land that was transferred into desertification land as abandoned cultivated land, which were all dominated by the slight, moderate, and severe desertification lands. Due to the lack of precipitation in the Mu Us Desert, the increased cultivated land from the reclamation on desertification land was mostly irrigated using large-scale sprinkler irrigation machines by extracting groundwater in recent years. Only the hydrogeological units with large water capacity and sufficient recharge can meet the water consumption (Shi et al., 2019). Previous studies have shown that, during the maize growing season, the contribution of groundwater for maize growth has reached 37.90% of the total water consumption in the Mu Us Desert, under the condition that the amounts of precipitation and irrigation were 214.10 and

177.00 mm, respectively (e.g., Bao et al., 2018). Therefore, the increased cultivated land from the reclamation on desertification land which needs long-term irrigation would directly lead to the decline of groundwater level in the Mu Us Desert (Lu, 2022). The majority of the increased cultivated land from the reclamation on desertification land lacks protection from shelter forests and effective coverage, making it more susceptible to wind erosion in the windy spring season during the fallow period (Hoffmann et al., 2011; Abdulslam et al., 2015; Du et al., 2018). Previous studies have indicated that cultivation activities could accelerate wind erosion by 2–15 times (Li et al., 2019). All of these indicated that the increased cultivated land from the reclamation on desertification land faces a potential remobilization risk and further affects the safety of cultivated land in China.

Since 2000, there has been an overall reversal trend of desertification land in the areas of the increased cultivated land from the reclamation on desertification land, and the decreased cultivated land that has transferred into desertification land as abandoned cultivated land. The effect of cultivation activities on desertification reversal seemed to be positive since 2000 (Tu et al., 2016; Xie et al., 2022). However, the developed desertification land exhibited a similar "increasing-decreasing-decreasing" trend as the reversed desertification land since 2000–2005. Compared to reversed desertification land, the more significant increase of developed desertification land from 2000–2005 to 2005–2010, and the less substantial decrease during 2005–2010, 2010–2015, and 2015–2020, suggest a potential remobilization risk in these lands (Fig. 7). In particular, both the developed and reversed desertification lands reached their maximum area proportions (2.86% and 20.36%, respectively) during 2005–2010. This highlights the presence of developed desertification land accompanying the desertification reversal process due to unsustainable human activities (Guo et al., 2020; Ngabire et al., 2022). Therefore, a cautious and stringent reclamation policy should be implemented to achieve a balance between new degradation and the reversal of past degradation, and to prevent secondary desertification in the Mu Us Desert (Alexander et al., 2018; Lu, 2022; Wei and Yan, 2022). Higher attention should be paid to desertification reclamation to avoid re-desertification and promote steady desertification prevention and control in the Mu Us Desert.

In this study, we extracted desertification land and land cover datasets from a series of Landsat images by the human-computer interaction visual interpretation method. Although the overall classification accuracy exceeded 95%, the extraction process was still subject to the influence of human experience and subjectivity. As a result, our findings have some limitations due to the research methods employed. Additionally, using single satellite data may not be as robust as multi-source data for providing policy recommendations. Future research should focus on the in-depth integration of multi-source data for better scientific references in policy formulation. Lastly, recent photovoltaic sand control projects in desertification areas (Liu et al., 2016) have not been considered separately in this study, which can be taken into account in future research.

5 Conclusions

Cultivation activities on desertification land can impact desertification degrees. In this study, we focused on the Mu Us Desert to examine this effect. Our findings revealed that the total cultivated land in the Mu Us Desert experienced a fluctuating increase trend from 1975 to 2020. Moderate and severe desertification lands were the preferred choices for the increased cultivated land from the reclamation on desertification land, and slight and moderate desertification lands constituted the primary category of the decreased cultivated land that was transferred into desertification land as abandoned cultivated land. The impact of cultivation activities on desertification reversal was more significant than that on the development of desertification. In particular, the time consistency of the maximum area proportion of developed and reversed desertification lands and the variations of developed desertification land across different periods indicated a potential remobilization risk in the areas of the increased cultivated land from the reclamation on desertification land and the decreased cultivated land that was transferred into desertification land

as abandoned cultivated land.

In summary, both rapid reclamation on desertification land and continuous abandonment activities in cultivated land could increase the potential remobilization risk by directly lowering groundwater levels and exacerbating wind erosion, respectively. Desertification of cultivated land could further intensify reclamation and abandonment activities, undermining the effectiveness of desertification prevention and control measures. As such, it is recommended that local governments in agro-pastoral ecotone areas make strict policies regarding desertification control and cultivated land use to achieve stability and sustainability in both land use and the environment.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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